Materials Science, Vol. 42, No. 4, 2006

SPECIFIC FEATURES OF THE INFLUENCE OF HYDROGEN ON THE PROPERTIES AND MECHANISM OF FRACTURE OF THE METAL OF WELDED JOINTS OF STEAM PIPELINES AT THERMAL POWER PLANTS

O. Z. Student, A. D. Markov, and H. M. Nykyforchyn

UDC 621.181:669.018

We study the standard tensile mechanical properties of a live-steam pipeline operated for about $2 \cdot 10^5$ h and model (repair) welded joints. As a result of the degradation of weld metal under service conditions, its strength becomes lower than that of base metal. We show that the unregulated orientation of specimens along the axis of a welded joint is the most acceptable for detecting the degradation of weld metal. Cathode polarization facilitates evaluating the state of the degraded weld metal and that of the base metal. We have also disclosed the specific features of the influence of internal (preliminary hydrogenation) and external (electrolytic hydrogenation in the course of tests) hydrogen on the properties and mechanisms of the fracture of weld metal.

The length of steam pipelines of thermal power plants (TPP) is calculated in kilometers, along which there are straight-line parts, bends, taps, knees, T-joints, reducers, expansion loops, etc. It is clear that one cannot manufacture such a system of pipes, branched in space, without welding. At the same time, welded joints (WJ) are the most vulnerable elements of any large engineering structures. In particular, the serviceability of live-steam pipelines of TPP to a significant degree is determined by the severe temperature-force conditions of their work in an active hydrogenating medium. Indeed, they operate at temperatures up to 565°C, are loaded with the internal steam pressure (up to 24 MPa), compensating stresses due to temperature expansion, and the dead weight of pipes, accessories, and insulation, and, finally, are subjected to stationary (during the base-load operation of power units) and variable (stops in the course of operation) loads, vibrations due to the fluctuations of steam flow in pipelines, and dynamic loads induced by the rotation of unbalanced pump rotors [1]. As to WJ, the influence of high-gradient fields of residual stresses [2], the macroinhomogeneity of composition, structure, and properties [3, 4], and high hydrogen content in the weld metal [5–7] are here additionally imposed on the severe operating factors mentioned above. These features advance rigid requirements to evaluating the serviceability of WJ at steam pipelines [8]. Obviously, this is possible only with the use of a database on the properties of base (BM) and weld metal (WM) of welded joints after their operation for different time at the steam pipelines of TPP. Despite the fact that the properties of degraded steam-pipeline steels were investigated earlier [9, 10] and are actively studied at present [11–13], this problem remains practically open as to WJ. In the present work, we continue our investigations of WJ after operation, begun earlier [14]. Our aim is to evaluate the mechanical properties and mechanisms of fracture of the metal from different zones of operated and repair WJ under the action of internal (absorbed by the metal prior to its loading) and external (coming to it in the course of active loading) hydrogen.

Subject of Inquiry and Testing Procedures

We tested the metal from different zones of a WJ at the vertical part of a live-steam pipeline of TPP, made of 15Kh1M1F steel and destroyed after $\sim 2 \cdot 10^5$ h of operation. Information on the subject of inquiry is pre-

Karpenko Physicomechanical Institute, Ukrainian Academy of Sciences, Lviv.

Translated from Fizyko-Khimichna Mekhanika Materialiv, Vol. 42, No. 4, pp. 26–35, July–August, 2006. Original article submitted July 19, 2006.

sented in [14] in more detail. For the sake of comparison, we also studied the metal from a model WJ, manufactured by manual electric arc welding according to the technology of carrying out repair welds accepted at TPP. The base metal under study was operated from one side of this joint and remained in the initial state from the other. Hence, the WM in this WJ did not work, and, therefore, we assumed that it was in the initial state. Thus, we can compare the mechanical properties of the metal from different zones of a WJ in the initial state and after long-term operation.

To evaluate the state of the metal, we used the characteristics of strength and plasticity under uniaxial tension envisioned by the normative documents currently in force. Smooth cylindrical specimens of diameter 3 mm were stretched on a UME-10TM machine with a velocity of the active clamp of $3 \cdot 10^{-3}\ \text{sec}^{-1}$. The mechanical properties were determined as the arithmetic mean of three–five tests. We cut out the specimens for experiments in two directions with respect to the WJ:

(i) transverse to its axis, in such a way that the zone chosen for studies is situated in the middle of working part of the specimen;

(ii) along the axis, in such a way that all working part of the specimen be in the chosen zone of the WJ, except the metal of the heat-affected zone.

The first variant corresponds to the requirements of the normative documents currently in force [15], and the second is not provided by it.

We compared the mechanical properties of the metal from different zones of welded joints in air (without and after preliminary electrolytic hydrogenation) and in a medium (with hydrogenation in the course of loading). Electrolytic hydrogenation was carried out in 5% sulfuric acid solution with addition of 0.05% of sodium thiosulfate. To change the intensity of hydrogenation, we used different current densities (10 and 50 mA/cm^2). Further, different duration of electrolytic hydrogenation (1 and 0.25 h) enabled us to vary the amount of hydrogen in the metal. To detect the influence of internal hydrogen on the mechanical properties of operated and nonoperated metal, we also tested specimens after annealing in vacuum for 2 h at a temperature of 570°C, which corresponds to the maximum possible temperature for steam pipelines during their operation.

The mechanisms of fracture of the specimens after tests for uniaxial tension were investigated on a scanning microscope. The fracture surfaces were cleaned by ultrasound.

Experimental Results and Discussion

Manifestation of the Degradation of the Metal of WJ under Service Conditions. The results of tensile tests of transverse specimens in air show (Fig. 1a and b) that, as a result of operation, the strength characteristics of WM decrease more than those for BM. Furthermore, the strength of WM exceeds substantially the strength of BM in nonoperated WJ, but becomes even somewhat lower in operated ones. This result is in good agreement with our conclusion, made earlier [14], that the hardness of WM after operation is lower than that of BM.

Hence, due to degradation under service conditions, WM no longer satisfies the regulated requirements to its strength, which would have to exceed the strength of BM. We compared the mechanical properties of the metal from operated and repair WJ in air by the degradation factor λ, which is equal to the ratio between the corresponding mechanical characteristics of operated and nonoperated metals. After operation, the characteristics of strength and plasticity decrease for both BM and WM (Fig. 1c). However, if this decrease is small for BM (σ_u by 11%, $\sigma_{0.2}$ by 10%, δ by 7%, and ψ by 4%), it is more significant for WM (σ_u by 28%, $\sigma_{0.2}$ by 45%, δ by 25%, and ψ by 12%). These results enable us to assert that since the service conditions are equal, WM degrades more intensely than BM. Hence, one can evaluate the degradation of WM not only by the local parameters of cyclic crack resistance, which is valid for BM [11], but also by the integral mechanical properties.

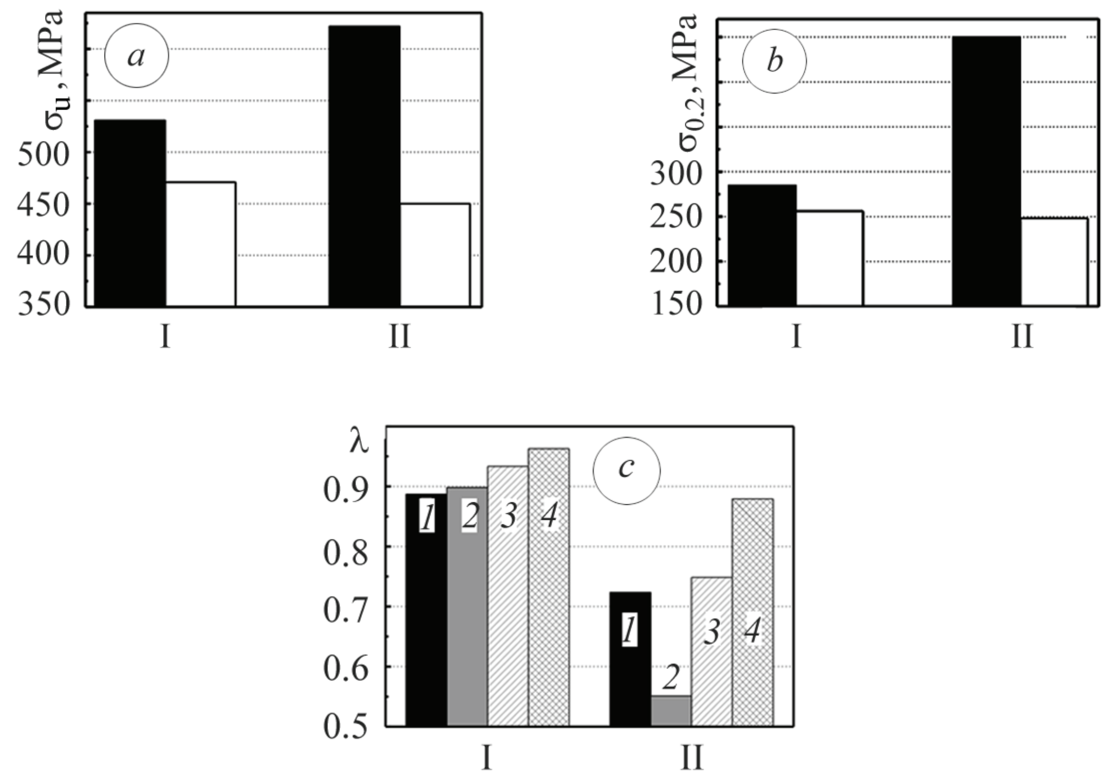

Fig. 1. Changes in σ_u (a) and $\sigma_{0.2}$ (b) for operated (light bars) and nonoperated (dark bars) metal and degradation factor λ (c) for σ_u (1c), $\sigma_{0.2}$ (2c), δ (3c), and ψ (4c) for BM (I) and WM (II) in tests in air.

Influence of the Direction of Cutting out the Specimens. The choice of the scheme of cutting out the specimens from actual pipes is regulated by [15]. It is clear that these requirements were substantiated for specimens cut out from nonoperated pipes. However, it is not known for the present to what extent the properties of the metal degraded under service conditions change equally in different directions and whether changes in the mechanical properties along an unregulated direction are not more substantial. Indeed, if the sensitivity of the metal to degradation according to the standard mechanical characteristics proves to be higher for specimens cut out in an unregulated direction, then this will give every reason to recommend a certain unregulated scheme of cutting out for evaluating the state of degraded metal by the integral parameters. To answer this question, we cut out specimens from different zones of repair and operated WJ in three directions (Fig. 2). The specimens for tensile tests in BM were oriented in the longitudinal section of welded pipes transverse to and along their axes. For WM, the specimens were placed along and transverse to the WJ axis (in what follows, we ascribe orientations 1 and 2 to transverse and longitudinal specimens, respectively) as well as in the cross section of a pipe in such a way that the specimen axis is perpendicular to the pipe radius (orientation 3[1]).

The results of tests of the specimens with different orientation in air show that, as to the strength characteristics, the unregulated transverse specimens with orientation 1 are the most sensitive to changes in WM due to the degradation of WJ under service conditions (Fig. 3). Hence, one should use exactly this variant for evaluating the state of operated WM. At the same time, longitudinal specimens with orientation 2 are widespread in power engineering for testing the state of the metal, but, according to the results obtained, they are not in the least suitable for this purpose.

[1] These investigations were carried out by S. Stepanyuk, senior researcher of the Institute of Electric Welding, Ukrainian Academy of Sciences.

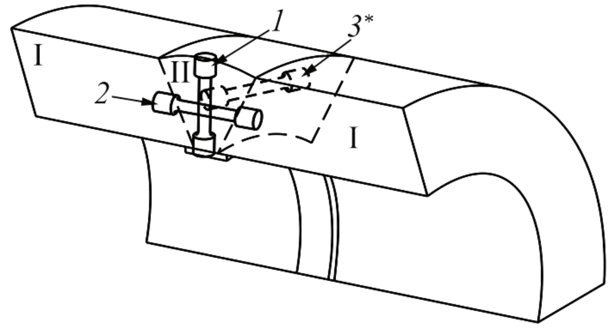

Fig. 2. A fragment of the steam pipeline with a WJ and scheme of cutting out the specimens from WM in different directions for tensile tests: ($1-3^*$) directions of cutting out the specimens, (I) BM, (II) WM.

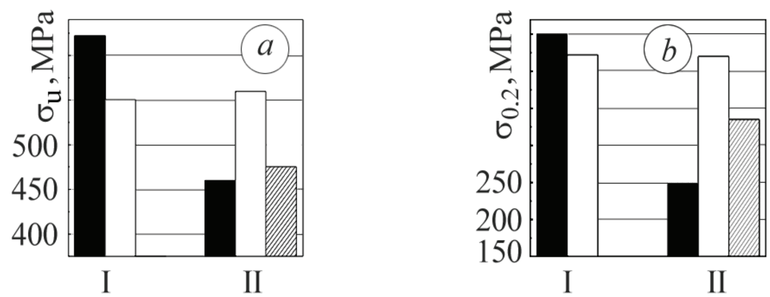

Fig. 3. Comparison of the strength characteristics of WM in repair (I) and operated (II) WJ in the course of tests in air, determined on specimens with orientations 1 (dark), 2 (light), and 3 (dashed bars).

On the example of a repair WJ, we studied also the influence of preliminary hydrogenation with subsequent testing in air (internal hydrogen) and hydrogenation in the course of tests (external hydrogen) on the changes in the mechanical properties of operated and nonoperated BM and WM. We used here transverse (orientation 1) and longitudinal (orientation 2) specimens. The difference between the influence of the direction of cutting out the specimens on the characteristics of strength and plasticity for both BM and WM manifests itself already in air (I). For example, we observe somewhat higher values of all parameters determined on longitudinal specimens (orientation 2) for both BM (Fig. 4, right and left columns), whereas, for WM in air (I), only the plasticity characteristics corroborate this rule, but the strengths become lower (Fig. 4, middle column). For BM, this can be a manifestation of the influence of the direction of pipe deformation in the course of its manufacture. However, the tendency of change in the strength of WM (Fig. 4b and e), opposite to BM, is a result of the higher defectiveness of the former transverse to the WJ axis than along it. This means that the cohesive force along the boundaries of WJ beads imposed onto one another is higher than the force along the boundaries of adjacent beads.

It is clear that, in the case of hydrogenation of the metal, these inhomogeneities have to manifest themselves more strikingly. In particular, for both BM under the action of hydrogenation [preliminary (II) and in the course of tests (III)], despite a decrease in the plasticity characteristics, we recorded their additional lowering on transverse specimens (Fig. 4, right and left columns). Only the data on δ for operated BM represent an exception. This can be a result of microdamages in the metal due to creep, which favor more rapid strain localization in the maximally weakened cross section. Irrespective of the direction of cutting out the specimens, the influence of external hydrogen is more appreciable than that of internal. Under the action of internal hydrogen, the influence of the direction of cutting out the specimens on the plasticity characteristics becomes substantially weaker in operated BM. Probably, this is evidence of the fact that internal hydrogen can interact here with any defects, in particular, structural ones (interfaces of sulfides located beltwise along the pipe axis) and micropores, formed as a result of creep. The latter appear on the grain boundaries, perpendicular to the direction of action of tensile stresses, which induce creep under service conditions. Taking into account the order of grain sizes (10 to 30 μm), we may conclude that the orientation of specimens in operated BM becomes less important for the manifestation of the influence of internal hydrogen on the integral characteristics.

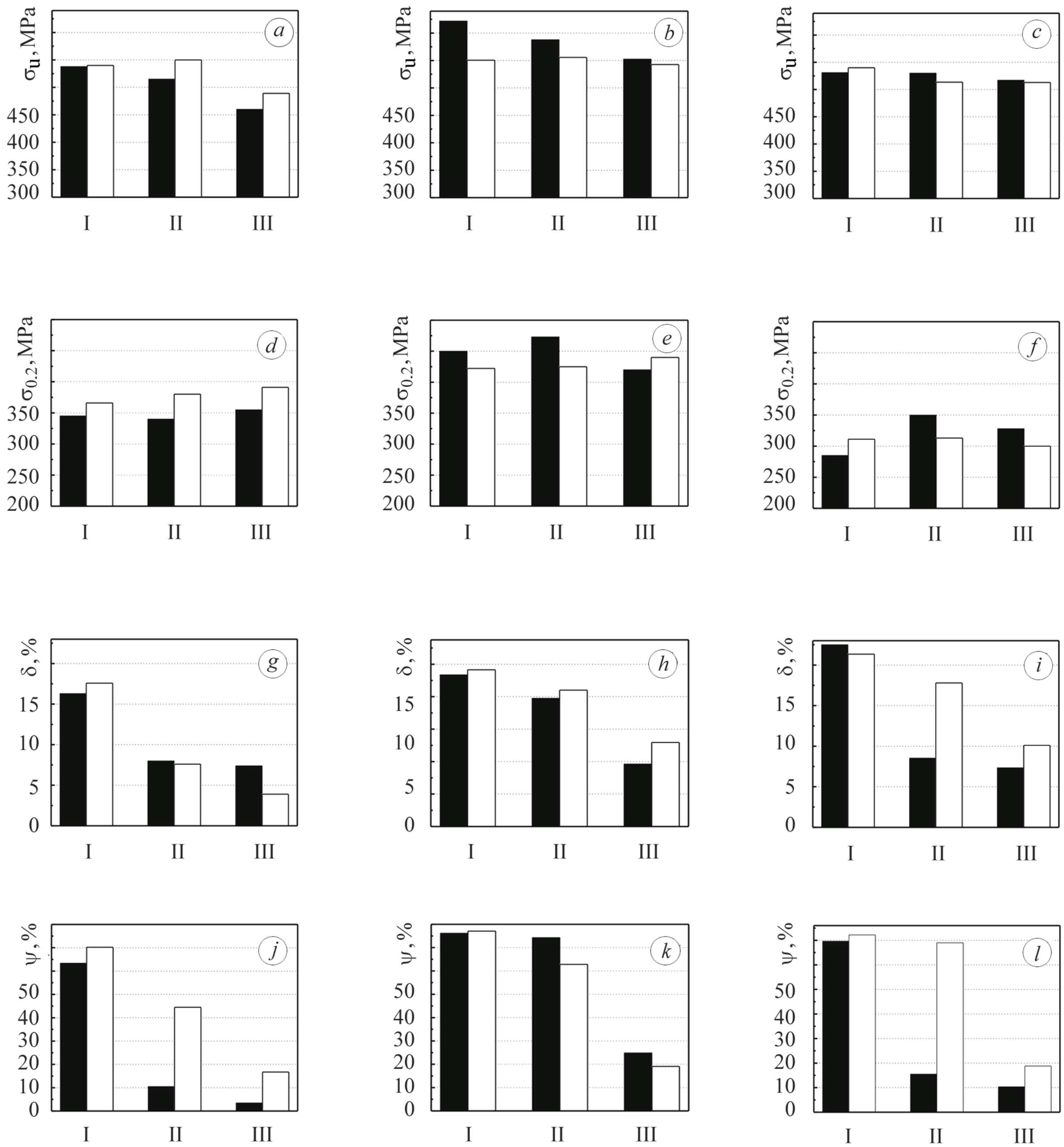

Fig. 4. Mechanical properties σ_u (a–c), $\sigma_{0.2}$ (d–f), δ (g–i), and ψ (j–l) for operated (a, d, g, j) and nonoperated BM (c, f, i, l) and WM (b, e, h, k), determined on transverse and longitudinal specimens (dark and light bars, respectively) in air (I), after preliminary hydrogenation for 1 h (current density 10 mA/cm^2) and fracture in air (II), and after preliminary hydrogenation for 0.25 h (current density 50 mA/cm^2) and fracture under hydrogenation (III).

It should also be noted that, under the action of both internal and external hydrogen, the strength characteristics are higher on longitudinal specimens for operated BM and, on the contrary, on transverse specimens for nonoperated. This feature can be explained by the absence of decohesion along the interfaces between elongated sulfide precipitates and the matrix, but this phenomenon takes place in nonoperated BM. In addition, the strength characteristics of both operated and nonoperated BM practically do not respond to the action of hydrogen on longitudinal specimens, whereas, for transverse ones, the strength of operated BM decreases even under the influence of internal hydrogen. Note that, on transverse specimens, the $\sigma_{0.2}$ value for nonoperated BM increases under the action of both internal and external hydrogen, and internal hydrogen manifests itself even more strongly (Fig. 4a). For operated BM, this effect disappears completely.

The analysis presented above enables us to conclude that hydrogenation can be considered a means for detecting the degradation of BM under service conditions by the integral mechanical characteristics.

Comparing the influence of hydrogenation on nonoperated WM, which has contacted with operated BM in the course of welding, we observe a tendency to change in the strength, similar to that for nonoperated BM. For transverse specimens (orientation 1), it is somewhat higher than for longitudinal specimens (orientation 2), which remain practically insensitive to hydrogenation (Fig. 4, middle column, bars II and III). A slight increase in $\sigma_{0.2}$ on transverse specimens is also preserved, but only under the action of internal hydrogen. External hydrogen decreases somewhat the $\sigma_{0.2}$ value for transverse specimens, which can be a consequence of the higher macroinhomogeneity of WM as compared with nonoperated BM. Under the action of hydrogen, the plasticity characteristics of WM change in different ways depending on the direction of cutting out the specimens. If δ on transverse specimens is lower than on longitudinal specimens under the action of both internal and external hydrogen, then the ψ value, on the contrary, is higher. The latter distinguishes nonoperated WM from the same BM. Furthermore, internal and external hydrogen decreases more strongly the parameter δ on transverse specimens and ψ on longitudinal specimens. This fact enables us to assume that the qualitatively different effect of hydrogen on the δ and ψ values for WM specimens having different orientations is a result of the predominant influence of different strength of the boundaries between WJ beads in two mutually perpendicular directions.

Comparison of the Effect of External and Internal Hydrogen on the Mechanical Properties under Tension. As is well known, the hydrogen content is fairly high even in nonoperated WM, and hydrogen penetrates into the metal in the course of welding, precipitating on structural and macrodefects. Under loading, it migrates to the domains with volume tension and, hence, can affect the mechanical properties. Therefore, to evaluate the effect of degradation on the mechanical properties of the metal just as it is, one should abandon the action of internal hydrogen, absorbed by the metal in the course of welding and operation, and take into account its properties after degassing in vacuum. Testing transverse specimens (orientation 1) in air, we compared the mechanical properties of operated and nonoperated WM. For this purpose, we used the factor λ, characterizing the relative change in the corresponding properties of the metal without degassing with respect to the metal degassed in vacuum. By the change in this factor, we judged, first, the influence of internal hydrogen on each of the mechanical characteristics and, second, the level of degradation of the operated metal. This comparison of the properties of WM from repair and operated WJ in air, obtained on transverse specimens (orientation 1) without vacuum annealing and after it, shows that the strength characteristics of WM in a repair weld, as compared with that annealed in vacuum, remain almost invariable ($\sigma_{0.2}$ and ψ) or even grow somewhat (σ_u and δ) but decrease in an operated WJ (σ_u by 10%, $\sigma_{0.2}$ by 20%, δ by 30%, and ψ by 8%). Hence, hydrogen in WJ does not change or even improves somewhat the characteristics of nonoperated WM but deteriorates all mechanical characteristics of operated WM (Fig. 5). This feature can be explained by the higher defectiveness of operated WM and, as a consequence, by the higher hydrogen concentration in it. Thus, we have recorded opposite tendencies of changes in the characteristics of nonoperated and operated WM under the action of hydrogen, absorbed by the metal in the course of welding and operation.

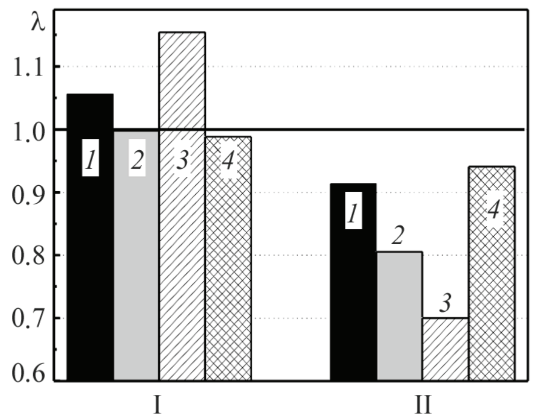

Fig. 5. Effect of the degassing of WJ in vacuum on σ_u (1), $\sigma_{0.2}$ (2), δ (3), and ψ (4) for nonoperated (I) and operated WM (II) according to the factor λ of relative change in these parameters (tests in air).

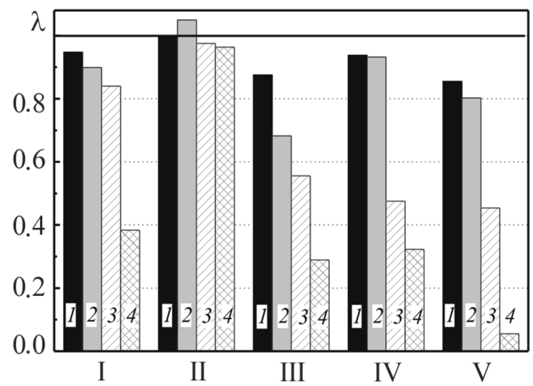

Fig. 6. Changes in the factor of hydrogen effect λ [relative change in the corresponding properties for preliminarily hydrogenated transverse specimens in air (I–III) and hydrogenated in the course of deformation (IV, V) with respect to those degassed in vacuum] on σ_u (1), $\sigma_{0.2}$ (2), δ (3), and ψ (4) for WM from operated (I) and repair WJ (II–IV) and for operated BM (V) from repair WJ. Conditions of hydrogenation: 1 h with a current density of 10 mA/cm^2 (I, II) and 0.25 h, 50 mA/cm^2 (III–V).

Further, we analyzed the mechanical properties of the metal from repair (nonoperated) and operated WJ by the factor λ, which in this case characterizes changes in the corresponding properties of the metal after preliminary hydrogenation with subsequent testing in air relative to the results obtained after vacuum annealing. The data of these studies show that, the conditions of hydrogenation being equal (preliminary hydrogenation for 1 h with a current density of 10 mA/cm^2 and subsequent fracture in air), the effect of internal hydrogen on the strength characteristics of WM of a repair WJ is slight but positive, whereas its influence on the WM of an operated WJ is substantially stronger and positive (Fig. 6). Only after preliminary hydrogenation of nonoperated WM with higher current density (50 mA/cm^2 for 0.25 h) do all its mechanical properties under the action of internal hydrogen become worse. This is evidence of the fact that the severe conditions of hydrogenation of even nonoperated WM can degrade its properties in air more strongly than 20-year operation of the metal at a steam pipeline.

We compared the influence of external and internal hydrogen on the mechanical properties on a repair WJ and obtained absolutely unexpected results (Fig. 6, III and IV). First, whereas all mechanical characteristics of

BM decrease more intensely under the action of external hydrogen as compared with internal (Fig. 4, right and left columns, and Fig. 6, V), which is in good agreement with the well-known concepts, we observe an opposite tendency for WM. In addition, according to all parameters (except δ), the action of external hydrogen on WM is weaker than that of internal hydrogen. This result is surprising because the amount of hydrogen coming to WM in the course of deformation is undoubtedly greater than that in the case of preliminary hydrogenation. Possibly, the difference between the influence of internal and external hydrogen is connected not only with the amount of hydrogen taking part in fracture but also with its redistribution in stressed WM. Owing to the adsorption of external hydrogen, slip bands more easily reach the lateral surface of specimens. In addition, the height of relief formed by these bands grows, and their density decreases as compared with those obtained in the course of tension in air, and this occurs under lower stresses. As is well known [16], hydrogen can carry dislocation along slip bands. This phenomenon favors the formation of surface segmental cracks by the exfoliation mechanism, and they, in turn, localize substantially the processes of deformation, decreasing the actual cross section of the specimen where fracture takes place. Hence, external hydrogen penetrates permanently into the metal and is localized in the zone with the maximum tensile stresses near the tips of segmental off-surface cracks. Its influence manifests itself in the stable propagation of these cracks, and lower strength characteristics are evidence of the fact that external hydrogen facilitates this process in BM with more or less uniformly distributed structural defects, which, in this case, represent grain boundaries and belt-like sulfide precipitates. At the same time, for WM, whose bead macrostructure already provides for the macrodistribution of defects, the influence of external hydrogen is localized on these defects. Here, the frequency of formation of off-surface cracks along the working part of specimens decreases, and the distance between them grows. The propagation of these cracks leads to a decrease in δ. At the same time, the significant distance between the cross sections where these surface cracks are located complicates their coalescence with the formation of a fracture surface, and this explains somewhat higher ψ values under the action of external hydrogen. As to the higher strength characteristics, this fact can only be connected with the hardening effect of external hydrogen on the surface layers of specimens from WM.

In the course of preliminary hydrogenation, the metal accumulates hydrogen and then, as the specimens are subjected to tension in air, loses it owing to hydrogen outlet to free surfaces. Hydrogen from the subsurface layers of the specimen passes to the atmosphere and, in the internal volumes of the metal, migrates and is localized on the nearest defects. The defects around which there exist local (on the interfaces between the matrix and various inclusions) or integral (in the central part of cross section of the specimen neck) bulk tensions are the most favorable for the location of hydrogen. Exfoliations on the matrix–inclusion interfaces favor the "molization" of hydrogen in the cavity, which increases the pressure in it. It is clear that if this assumption is valid, the combined action of stresses and molecular hydrogen has to lead to the appearance of brittle fragments of the relief in the fracture surface, which differ from those characteristic of plastic fracture during tests in air.

Fractographic Features of the Influence of External and Internal Hydrogen. In the case of electrolytic hydrogenation both prior to and during the tests, the effect of hydrogen is significant in the zone of bulk tension in the central part of the cross section of the specimen (internal hydrogen) and from the generating line of its surface (external hydrogen). Possibly, under such conditions, the expenditures of energy for the initiation of local damages from the generating line of the surface of specimens made of operated and nonoperated metal are practically equal. Indeed, fracture from the surface of specimens is stimulated by practically identical hydrogen flows along slip bands. Fractographic analysis of the fracture surfaces of specimens in the case of their electrolytic hydrogenation shows that there are practically always numerous local germs of failure from the lateral surface of specimens, irrespective of which zone of a WJ the metal was taken. Under tension, these germs coalesce due to the plastic fracture of diaphragms between them. In the core of fracture surfaces, in addition to ductile elements of the pit relief, one can sometimes observe circular brittle domains with pits at their centers and a characteristic radial orientation of the crests of breaking-off, which separate the domains of local spallings in parallel but distant in space planes (Fig. 7a). These elements can be a manifestation of the effect of internal hy-

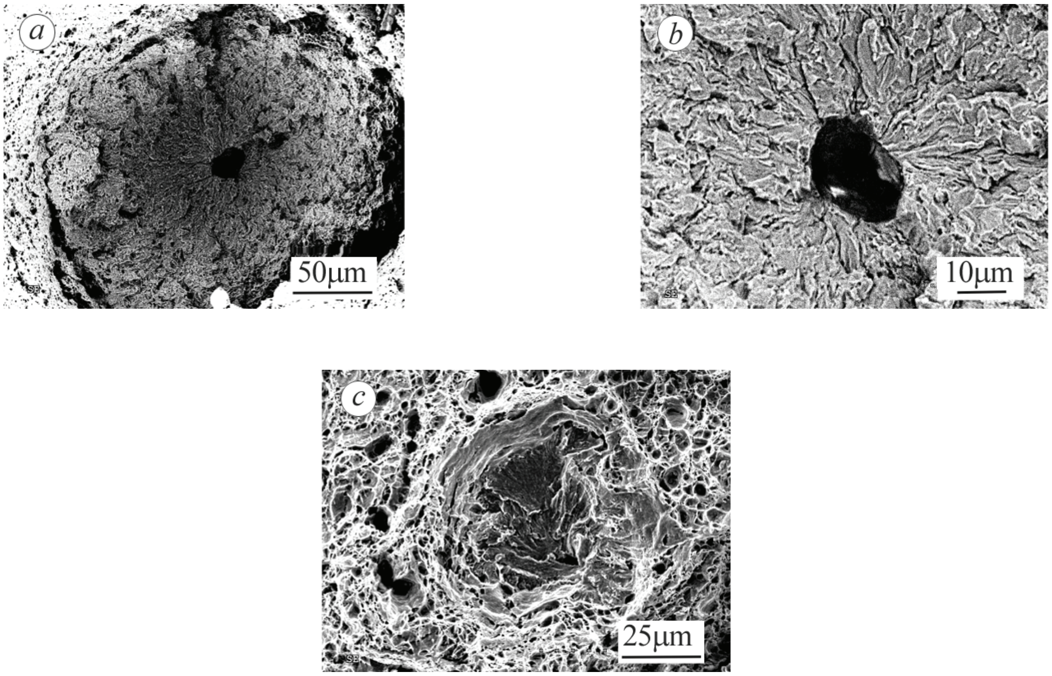

Fig. 7. Fractographic features of the fracture surfaces of preliminarily hydrogenated specimens from WM (a, b) and BM (c) after tensile tests in air.

drogen, which, migrating to the region of three-dimensional stressed state, forms molecules on defects and, creating a high pressure, leads to such local failures. To check this hypothesis, we investigated the fracture surfaces of specimens from different zones of a WJ, tested after preliminary electrolytic hydrogenation but in air. In these tests, we excluded the penetration of hydrogen into the metal along slip bands, and only the effect of internal hydrogen remained. The results obtained show that, despite the macroductile character of fracture surface of the cup-cone type, in its central part, against a background of the typical pit relief, there are different-sized, practically circular domains of spalling character with holes at their centers (Fig. 7b and c). Since nothing of the kind was recorded in nonhydrogenated metal, it is logical to assume that these elements of fracture surfaces are a manifestation of the action of internal hydrogen. Note that their quantity is greater, but their sizes are smaller than in the case of combined action of external and internal hydrogen. Furthermore, these features of the relief in nonoperated metal should be considered an exception, whereas they predominate in operated one, and, hence, their area could serve as a quantitative fractographic indicator of the state of degraded metal.

CONCLUSIONS

Due to degradation under service conditions, weld metal no longer meets the requirement concerning its higher strength as compared with BM. The results of testing specimens with different orientation in air show that, as to the strength characteristics, unregulated transverse specimens are the most sensitive to changes in WM induced by their operation. Longitudinal specimens, which are used most often, are of little avail for this purpose. Hydrogenation enables one to enhance substantially the sensitivity of evaluating the state of operated WM and to judge the state of BM, degraded under service conditions, according to the integral mechanical properties, which cannot be realized without hydrogenation. We have recorded opposite tendencies of changes in the mechanical properties of operated and nonoperated WM under the action of hydrogen, absorbed by the metal in the course of welding and operation. We have also determined the specific features of the influence of external and internal hydrogen on the mechanical properties of WM. Finally, the mechanism of manifestation of the action of internal and external hydrogen has been disclosed on the basis of fractographic analysis.

This work was carried out within the framework of the purposeful complex program of the Ukrainian Academy of Sciences “Problems of the working life and safe operation of structures, buildings, and machines” (RESURS) and the regional program “Determination of the residual life of structures, buildings, and machines of long-term operation and development of measures for extending the term of their safe work for 2001 – 2010.”

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